A Systems Engineering Tool for Small Satellite Design

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Abstract. The growing popularity of small satellites for applications of all kinds has lead to a marked increase in the number of requests from customers of The Aerospace Corporation for studies involving small satellites. The existing design tools used by the Corporation for concept evaluation of large spacecraft have, in many cases, proven inadequate for these small spacecraft studies. As a result, Aerospace is developing a systems engineering tool to support the conceptual design of small satellites.

The Aerospace Corporation's small satellite systems engineering tool utilizes a spreadsheet-based approach to efficiently track information regarding the mass, power, and volume of the satellite subsystems. This subsystem information is derived through a variety of means, including analytical relationships, iterative solvers, and databases of components appropriate for small satellites. Physics based models for such factors as solar illumination and external torques have been incorporated into the tool to aid in the analysis of the design.

In addition to data tracking, the spreadsheet approach used makes it easier for a concurrent engineering methodology to be applied to the design process. This means the effects of a change in one subsystem are immediately propagated to the other subsystems, and system-level effects are more easily identified. The end result is a tool that facilitates rapid systems-level concept evaluation and trade-space exploration in support of the small satellite design process.

This paper describes The Aerospace Corporation's small satellite systems engineering tool. The approach underlying the tool, as well as an overview of the implementation, relationships between the subsystems, and the flow of information are presented.

Introduction

A growing number of future space missions, for either programmatic or technical reasons, require small, low-mass, low-cost satellites. Interest in these new mission concepts is encouraged by the perception that a small satellite can be both capable and low-cost. As a result, more small satellites are being formally studied at the conceptual stage of many civil, commercial, and military programs than have been in the past. Figure 1 clearly illustrates the impressive growth in the number of small satellites launched over the last two decades, particularly at the smaller (<25kg) end of the size spectrum. Both civil and military space programs have launched research and development efforts focused on small satellites. Examples include NASA's Space Technology 5 *Nanosat Constellation Trailblazer*, and the Air Force Research Laboratory's *Technology Satellite of the 21st Century* (TechSat 21) and *MightySat* programs, which seek to test and prove technologies and architectures. Further advances in small satellite capabilities are being driven by research into new technologies such as microelectromechanical systems (MEMS)[1]. For example, The Aerospace Corporation's Center for Microtechnology is investigating a concept for future satellites, in which the entire spacecraft is fabricated on silicon, using a combination of MEMS components[2].

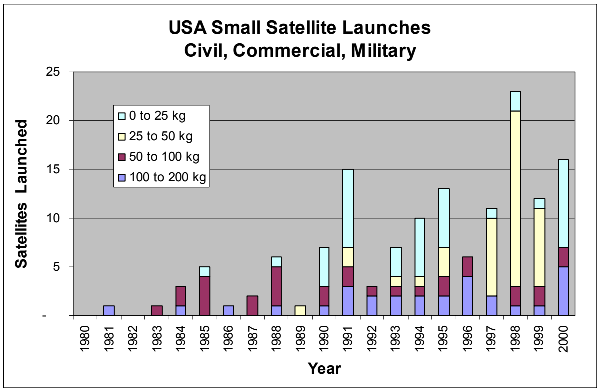

Figure 1 *Growth in small satellite launches*

It is well known that decisions made in the concept phase of a program can determine approximately 70% of the cost of a program[3]. The increase in small satellite launches, and the planned inclusion of small satellites in so many future programs, indicate a need for systems engineering tools to aid in the conceptual trade studies for these programs. These tools must be appropriate to small spacecraft and the new technologies from which they will be composed. The Aerospace Corporation (hereafter referred to as Aerospace) is presently working to develop such tools.

Small Satellite Systems Engineering

Systems engineering is concerned with the overall performance of a system for multiple objectives (e.g. mass, cost, and power). The systems engineering process is a methodical approach to balancing the needs and capabilities of the various subsystems in order to improve the performance of the system. The size, volume, and mass constraints often encountered in small satellite development programs, combined with increasing pressure from customers to pack more capability into a given size, make systems engineering methods particularly important for small satellites.

Spacecraft systems engineering is an established and well-understood discipline. However, many of the standard tools and techniques used to perform conceptual design of spacecraft contain implicit assumptions that are based on the characteristics of large satellites. This is a problem, since the characteristics of a small satellite can differ from those of traditional large satellites (Figure 2) in a number of ways:

- Small satellites often have fixed solar arrays instead of sun-tracking solar arrays
- Small satellites often do not have deployables
- Small mass leads to reduced thermal inertia
- Small size leads to reduced power generation and storage capabilities
- Volume can be tightly constrained
- Surface area can be at a premium
- Little historical data is available at the lower end of size spectrum (there have been relatively few programs, and those are not always well-documented), making parametric resource estimates difficult
- Small satellites use smaller components, new technologies (e.g. MEMS), and non-traditional vendors

These differences mean that although the process used to design small and large satellites is similar, the tools required to support the process are different.

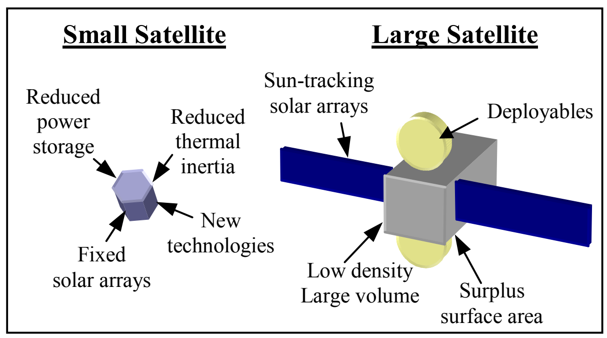

Figure 2 *Small Satellites vs. Large Satellites*

Concurrent Engineering Methodology

Traditional design methodology is a sequential, multidisciplinary process, and as such, has several disadvantages. Often, one subsystem cannot be designed until the results from another subsystem are available. Communication of design data from one subsystem specialist to another can be complex and time-consuming. Thus, due to the time required to complete a design iteration, the number of iterations that can be performed is very limited[4].

In an effort to improve upon the traditional sequential approach to design Aerospace has developed centralized design processes (Figure 3) based on a concurrent engineering methodology. Using this design process a systems engineer works with subsystem specialists to generate simplified subsystem design algorithms. The systems engineer compiles the information into a single spreadsheet-based tool known as a Concurrent Engineering Model (CEM). The systems engineer then uses the spreadsheet model to quickly design a spacecraft and examine possible design trades. Because the models and information for each subsystem are linked within the spreadsheet, the effect of any change is instantly seen by all of the subsystems. All of the subsystem requirements are considered simultaneously. The trade space that can be explored in a given amount of time is greatly expanded. The design cycle can be shortened from months to days or even hours.

The concurrent engineering approach to spacecraft design can also be used in a distributed mode, in which specialists operate individual subsystem spreadsheets that are linked via a network (Figure 3). This kind of distributed real-time design process has been successfully used in Aerospace's Concept Design Center[4] (CDC), as well as in other similar facilities such as JPL's Project Design Center (PDC). The distributed process has the advantage that the subsystem specialists remain in the loop during design iteration, allowing more complex subsystem design algorithms to be used. As a result, a distributed process can achieve a higher level of design fidelity than is typically available within the framework of a centralized design process.

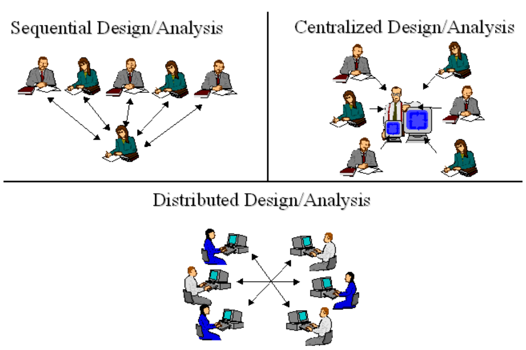

Figure 3 *Types of design process*

Aerospace has a dual approach to conceptual spacecraft design, with the choice of design process depending on the needs of the customer (Figure 4). The CDC is used when higher fidelity and direct interaction with the customer is desired. Specific trades are developed in detail. A CEM is used when a rapid answer is needed, a broad trade space is desired, and lower fidelity is acceptable. CEMs are usually developed for a specific type of mission (e.g. GEO communications spacecraft), and then modified and reused for later design studies.

	Sequential Design	Centralized (CEM)	Distributed (CDC)
Development Time	N/A	Very Short	Short
Result Production Time	Long	Very Short	Short
Trade Space Exploration	Limited	High	Moderate
Product Detail	Very	Limited	Moderate
Integrated by	Customer	Designer	Team
Process	Very Flexible	Flexible	Constrained

Figure 4 *Comparison of design processes*

Small Satellite Concurrent Engineering Model

Spacecraft conceptual designs prepared by Aerospace are used to support feasibility studies, program cost estimates, trade space explorations, and technology insertion studies. Aerospace has developed several systems engineering tools to support spacecraft conceptual design tasks, including a number of CDC teams, and a variety of CEMs. However, these tools are usually intended for designing large satellites, and thus incorporate assumptions that make the tools less effective in the small satellite regime.

In an effort to improve Aerospace's small satellite design capabilities, development of the Small Satellite Concurrent Engineering Model (SmallSatCEM) was initiated. The SmallSatCEM project aims to produce a tool that will aid systems engineers in performing conceptual-level design studies of small satellites. The SmallSatCEM is intended for use as a tool to generate point designs in support of conceptual design studies. Additionally, it is hoped that component and subsystem designers will find the tool useful in estimating performance requirements for new small satellite components that are in the development phase.

SmallSatCEM Goals

The primary goal of the SmallSatCEM project is to develop a useful tool that will allow satellite systems engineers to rapidly design and analyze a small satellite bus. A secondary goal is to develop the tool in such a way that it can be used widely within Aerospace. The SmallSatCEM is aimed at designing single spacecraft, and thus will not include capabilities such as constellation design. However, the SmallSatCEM could be used to derive a spacecraft design suitable for some pre-determined system architecture and constellation geometry.

There are a number of characteristics that contribute to the usefulness of a systems engineering tool[5], such as

- Relevance to the study being performed
- Credibility in the eye of the decision maker
- Responsiveness of the model
- Transparency
- User friendliness

The design of the SmallSatCEM addresses these desirable characteristics in various ways.

Since the tool is intended for use in small satellite design studies, a conscious effort has been made to avoid the inclusion of modeling assumptions that are relevant only to large satellites. The SmallSatCEM instead includes databases of components appropriate for small satellites, and physical models (such as solar illumination of fixed solar cells) that support the types of analysis needed for small satellite design. Additionally, attributes that are important in designing small satellites, such as volume and surface area, are tracked and reported. The development team is implementing standard models and equations[6,7] where they are appropriate, and validating the models against other tools wherever possible.

The subsystem models that are being implemented in the SmallSatCEM are intended to be simple enough to describe a design at the conceptual level, and yet provide sufficient detail to isolate the major system drivers within the spacecraft design. The SmallSatCEM team has made an effort to keep the models as general as possible in order to ensure that the tool is reasonably flexible. As an example, the astrodynamics model is not tied to a particular planet (the tool presently supports Earth and Mars as central bodies), and allows for elliptical orbits of arbitrary inclination.

The SmallSatCEM is being implemented in Microsoft Excel* as a single workbook, and makes extensive use of Visual Basic* to extend the capabilities of Excel. The decision to use Excel and Visual Basic was made for several reasons. A primary driver is that the use of Excel allows the SmallSatCEM team to rapidly develop a reasonably uncomplicated, user friendly, self-contained tool that can be easily distributed throughout Aerospace. The temptation to link with external programs has been expressly avoided because of the potentially limited availability of these programs to other users. Visual Basic is a full programming language so, in principle, any functionality of an external program can be duplicated. This is being done, although only to the level of fidelity that is needed for conceptual design. Another advantage of using Excel is that it is widely known and flexible enough that the SmallSatCEM can be expanded or customized by a user as needed. Unlike compiled software, the use of Excel with Visual Basic makes the internals of the tool easily accessible, and thus checking equations or updating models is very easy.

The SmallSatCEM is conceived as a single user tool, and it is intended that the user be able to complete a design without the need for intervention by a subsystem expert (although consultation with experts would obviously be beneficial, and is encouraged). To help the user rapidly specify a new spacecraft design the user interface layout of the spreadsheets is consistent throughout the Excel workbook. Diagrammatic representations of subsystem models are included to aid the user in understanding how the tool functions and how the required user inputs are used to specify the subsystem design.

Workbook Architecture

There are two major processes in an iterative design cycle: the progression from requirements through design to a design state, and the analysis of a specified design to determine its performance relative to requirements (Figure 5). This design, build, and test cycle can be applied both at the level of the whole spacecraft, and at the level of a single subsystem. Spacecraft studies at the conceptual level may involve one or both of these processes, depending on the goals of the study.

At the conceptual stage of a project the systems engineer is often faced with the task of designing a possible top-level architecture for a spacecraft to determine project feasibility. A typical approach to this task is to use the requirements of the payload to select some known hardware components (i.e. make system design decisions), thus leading to a spacecraft design. The arrow at the top of Figure 5 illustrates this process, in which the requirements lead, via design decisions, to a design "state". The state specifies the components of each subsystem, as well as mission details for the spacecraft, as determined from the design process.

Rather than proceeding from requirements to a design, a different question is often posed at the conceptual stage of small satellite projects: given a volume and mass constraint, what can be done with a small spacecraft of a given configuration, or what type of payload can be supported? A common variation on this question is: given a small satellite configuration, what

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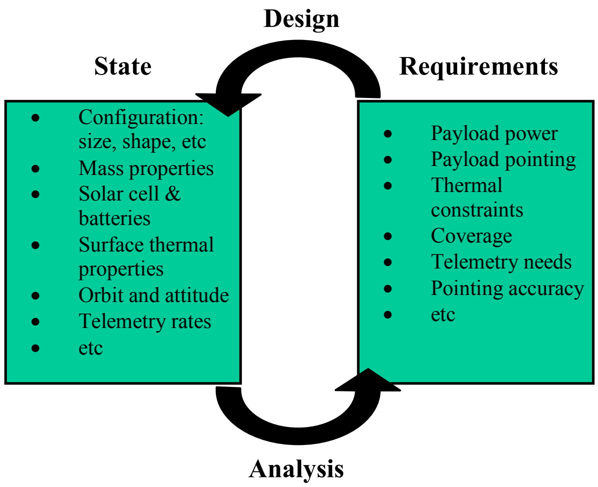

Figure 5 *Iterative Design Cycle*

subsystem miniaturization or new technologies need to be developed to make this system possible? Both of these questions are examples of a situation in which the state of a spacecraft is specified or hypothesized, and the requirements that can be supported by the spacecraft must be determined. The arrow at the bottom of Figure 5 represents this process of analysis, in which some aspect of the spacecraft or subsystems is simulated to determine performance.

A systems engineering tool for conceptual design must facilitate both the design and analysis processes in order to be flexible enough to deal with a large variety of design problems. With this in mind the Excel workbook that comprises the SmallSatCEM has been developed to explicitly reflect the cycle portrayed in Figure 5, and, as a result, incorporates a worksheet within the workbook dedicated to tracking the design state of the spacecraft. Orbit and payload requirements are captured on a separate worksheet, and flow from there to the worksheets used to describe each subsystem. The information flow within the workbook is depicted in Figure 6, which helps to illustrate the way in which the workbook structure maps to the iterative design cycle.

The workbook uses separate worksheets to describe, design, and analyze each subsystem. The worksheets each contain a specific section intended for use as a design tool, the outputs of which contribute to specifying the state of the spacecraft. The design tools consist of menu selections from databases of components (Figure 7), historical models built up from experience, and computation chains of physical models.

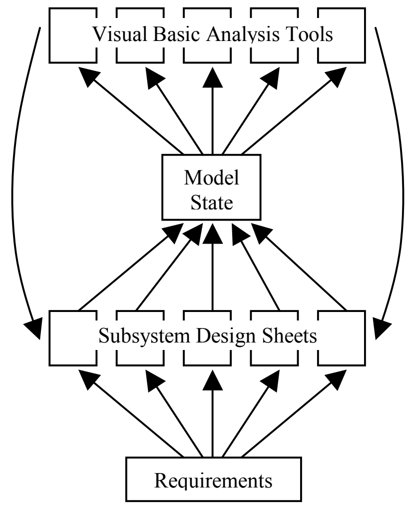

Figure 6 *Information flow within the SmallSatCEM*

The SmallSatCEM is being implemented such that it represents the spacecraft subsystems in terms of a limited set of pre-defined units (components or functional blocks), the parameters of which can be specified by the designer. Once state of the spacecraft design is defined in terms of these parameters a variety of analysis tools can be applied to simulate the performance of the design during mission operations. These analysis tools are largely implemented in Visual Basic, and answer specific questions about issues such as power production, disturbance torques, or telemetry access times.

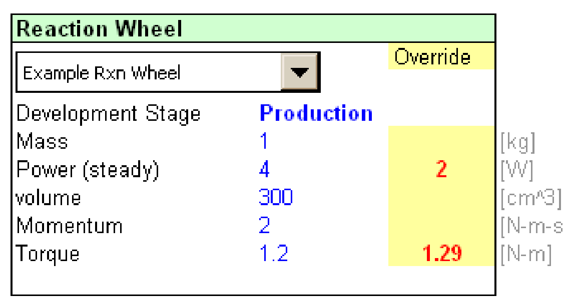

Figure 7 *Component selection from a drop-down menu*

The worksheets being implemented as part of the SmallSatCEM are: Payload & Mission, Configuration, Propulsion, Command & Data Handling, Communications (including telemetry, tracking & control), Attitude Determination & Control, Power, Mass Distribution and Properties, Thermal, Model State, Database, and Cost. A brief description of each worksheet will follow.

Payload & Mission

The payload is the purpose of the mission; this makes the payload requirements the driver for the entire design. Up to five generic payloads may be specified by providing system requirements such as mass, power, volume, slew requirements, stability, data rates, and so on. The payload requirements are passed on to each subsystem sheet, where they are used as a guide for subsystem design decisions. Also specified on the Payload & Mission sheet are the orbital elements for the initial, operational, and disposal orbits, and the desired operational attitude.

Configuration

The size and geometry of the spacecraft bus is specified on the Configuration sheet (Figure 8). Spacecraft geometry is limited to a right cylindrical polyhedron, for which the designer specifies a height, diameter, and number of sides. Up to 8 deployable "panels" can be specified in terms of size, location, and tracking mode. These panels can be used to simulate deployable solar arrays, antennas, thermal radiators, or gradient booms, depending on the specified panel shape.

Propulsion

The Propulsion sheet is divided into transfer propulsion and on-orbit propulsion sections. These systems are designed independently, using drop-down menus to select the thruster type and quantity for each system. The change in velocity (Δv) requirements are calculated from the orbit parameters defined on the Payload & Mission sheet. The propellant mass and tank size is then determined using an iterative solver.

Command & Data Handling

The Command & Data Handling subsystem sheet allows required data rates, compression ratios, and ground station contact duration information to be entered. From this information, storage, processing, and memory requirements are derived. Database selections can then be made for the Processor, Memory, Data Storage, and Input/Output interface needed to meet the derived requirements.

Configuration Design

Spacecraft Body Configuration Design Element	Units	Value
Number of Sides	-	6
Circular Diameter (cm)	cm	45
Height (cm)	cm	6
Length of Side (cm)	cm	22.5
Top or Bottom Area (cm^2)	cm^2	1315.3
Side Panel Area (cm^2)	cm^2	135.0
Total Surface Area (cm^2)	cm^2	3440.6
Body Volume (cm^3)	cm^3	7891.7

Deployed Panel Surfaces		Space			
Design Element	Units	13	14	16	
Surface Name	-	Panel 1	Panel 2	Panel 3	Pa
Included in Spacecraft	TF	☑	☐	☐	
Sun Tracking	-	1-axis	No	No	No
Panel Length (cm^2)	cm	400	12		
Panel Width (cm^2)	cm	100	4		
Panel Azimuth (deg)	deg	90	-90		
Panel Elevation (deg)	deg	0	0		
Panel Roll (deg)	deg	90	180		
Z - Axis offset of Panel	cm	20	20		
Radial Distance (in X-Y Plane) of Panel	cm	30	30		
Surface Area (cm^2)	cm^2	40000.0			

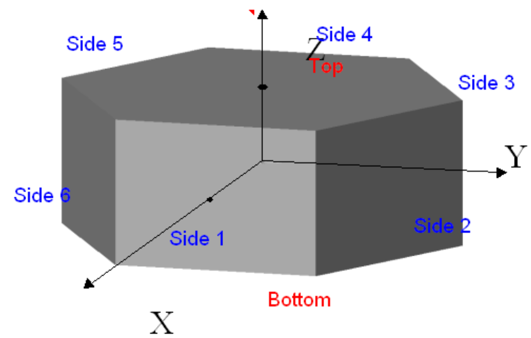

Figure 8 *Specifying a configuration*

Communications

The Communications subsystem is divided into telemetry, tracking & control up and downlinks, a data downlink, and crosslinks. The hardware that comprises each link is designed independently via database selection of components. A link analysis tool calculates losses, gains, power, antenna sizing, efficiencies, and so on.

Attitude Determination & Control

The attitude determination and control system (ADACS) is designed by selecting sensors and actuators from drop-down menus. Visual Basic code is used to simulate the disturbance torques acting on the spacecraft over one orbit (Figure 9). Using spreadsheet calculations the maximum values of the disturbance torques and the accumulated angular momentum are computed, and compared to the capability of the selected components. Control torque and/or thrust level requirements are also computed, based on the slew requirements of the selected payloads.

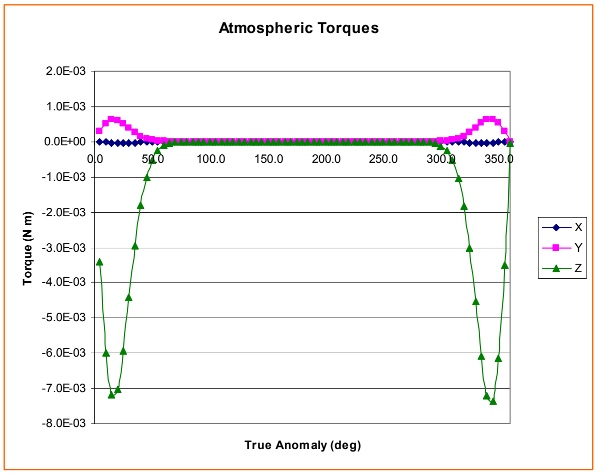

Figure 9 *Atmospheric disturbance torques*

Power

The Power sheet allows the designer to select the type of solar cells to be used for body-mounted or deployable arrays, as well as the battery type and bus voltage. Based on the types of solar cells and batteries selected, the solar array area and the battery mass needed to meet the power requirements of the spacecraft are computed. Since it cannot always be assumed that all of the solar arrays will be directly facing the sun, the Power sheet includes an analysis tool that simulates the solar illumination for each of the spacecraft body surfaces and deployable panels (Figure 10).

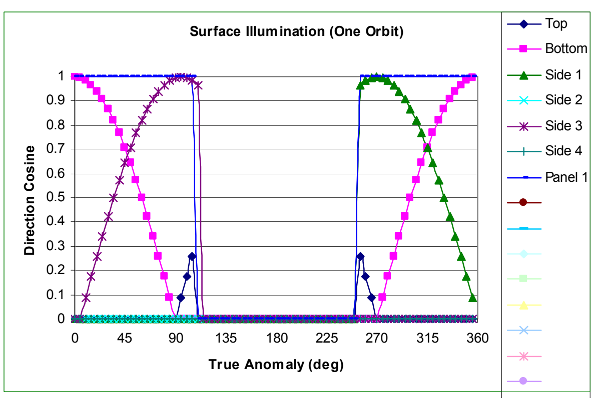

Figure 10 *Solar illumination for each spacecraft surface*

Mass Properties & Distribution

The Mass Properties & Distribution sheet provides the designer with a way to distribute the component masses on the different surfaces and panels of the spacecraft, as well as within several internal "zones". This mass distribution information can then be used for thermal modeling and sizing of the attitude control system. The bus structural material can also be specified on this sheet, via a database-driven drop-down menu. Given the mass distribution information, the centers of mass and mass-moments of inertia are calculated for each panel and for the entire spacecraft.

Thermal

The Thermal sheet treats each panel, body surface, and interior zone as a node. Conduction coupling factors are assigned between nodes. A thermal analysis can then be performed to determine the temperature of the different nodes. This analysis is compared to the minimum and maximum temperature requirements for the electronics and other components. Based on these analyses, additional surface area for radiating heat, or deployed radiators, can be assigned. The SmallSatCEM team is considering implementing several "pre-designed" thermal subsystem configurations to accommodate studies that are not yet at the level of detail required by the present thermal model.

Model State

All entered and calculated information from each worksheet is linked to the Model State sheet. As mentioned previously, this sheet contains the state of the spacecraft design. The Model State is the source of data for all of the analysis tools, as well as any subsystem sheets that require information on the present spacecraft design. This arrangement ensures that design data is consistent throughout the model.

Database

The Database sheet is a collection of tables of component data for a variety of different components. These tables act as the source of data for the drop-down menus used on the subsystem design worksheets. The databases contain three categories of components: traditional, research, and future or non-existing. At present, the data contained in these databases, particularly data on "traditional" components, requires modernization and population by components that are appropriate for small satellites. The ability to incorporate fictional components into the databases allows technology insertion scenarios to be studied, while still retaining a clear delineation between real and projected data.

Cost

The Cost model makes use of various parametric cost relationships that are derived from Aerospace's Small Satellite Cost Model[8,9]. However, many future small satellites may use non-traditional space components that cost relationships based on historical data are ill equipped to model. The lack of testing, handling, and government oversight make non-space-qualified hardware less expensive to purchase and assemble. A survey of non-space industry electronic components may be beneficial to assist in understanding how to better provide accurate cost relationships for non-traditional components.

Conclusions

Small satellites are becoming a popular choice for low-cost, rapidly developed space systems. The application of systems engineering methodologies to small satellite development will help to ensure that small satellites are not only low-cost, but fulfill their mission objectives. Existing tools for satellite systems engineering tend to be biased toward large spacecraft, and lack capabilities that are necessary for small satellite design. As a result, The Aerospace Corporation is developing a systems engineering tool, known as the SmallSatCEM, intended to support small satellite design studies.

The SmallSatCEM is implemented as a self-contained Microsoft Excel workbook, with a Visual Basic backend to handle complex tasks. The tool is intended to support the classical iterative design cycle, without the need to consult subsystem experts or gather data from external software. To this end, the workbook includes small satellite component databases, as well as physical models and analysis tools selected for their relevance to small satellite design tasks.

Development of the SmallSatCEM is ongoing. The SmallSatCEM team is working to complete and validate the existing SmallSatCEM design. Once the SmallSatCEM is fully implemented and in operation the development team will begin planning for the extensions or improvements that will invariably arise from actual real-world experience with the tool. Additionally, portions of the SmallSatCEM are being transitioned to the CDC, further enhancing the CDC's small satellite design capabilities.

As the development of the SmallSatCEM proceeds, the structure of the tool is becoming much more complex. This has caused concerns about the maintainability and robustness of the workbook. The Visual Basic backend, in particular, takes some effort to understand. It is hoped that an aggressive code cleanup and documentation effort will help to mitigate these problems.

Acknowledgements

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Biography for Allan I. McInnes

Allan I. McInnes is a member of the Vehicle Concepts Department at The Aerospace Corporation. He is primarily concerned with the conceptual design of space vehicles, and the development of systems engineering tools such as the SmallSatCEM. He has been involved in several studies examining future small satellite concepts, as well as studies supporting the MILSATCOM, SBR and GMSP programs. In addition to his work on the SmallSatCEM, Mr. McInnes is presently supporting a review of the design tools used in the PDC, as well as being involved in the JPL MER fault protection effort. Prior to joining The Aerospace Corporation, Mr. McInnes developed avionics test software for RJO Inc. He holds an MS in Engineering from Purdue University.

Biography for Daniel M. Harps

Daniel M. Harps is a member of the Vehicle Concepts Department at The Aerospace Corporation. His primary focus is the conceptual design of space vehicles. This includes the development and use of concurrent system design tools such as CEMs and the tools used in the CDC. Mr. Harps is currently a full-time graduate student at UCLA studying Micro-Electro-Mechanical Systems (MEMS), working part time at The Aerospace Corporation during the school year. He received his B.S. in Mechanical Engineering from Brigham Young University in 1999.

Biography for Jeffrey A. Lang

Jeffrey A. Lang is a member of the Vehicle Concepts Department at The Aerospace Corporation. He has been involved in several studies examining future small satellite concepts, as well as providing CAD support for programs such as SBIRS, C/NOFS, and NPOESS. Mr. Lang is currently a full-time student at California State University Long Beach studying Aerospace Engineering, working part time at The Aerospace Corporation during the school year.

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Dr. Charles M. Swenson is an Assistant Professor in the Electrical and Computer Engineering Department at Utah State University. He graduated with his Ph.D. in Electrical Engineering from Cornell University in 1992, and joined the faculty at Utah State University that same year. His research expertise is in experimental space science and space systems engineering, and his teaching responsibilities include the space systems engineering curriculum at Utah State. Currently Dr. Swenson is a principle investigator on USUSAT, and part of the ION-F team within the AFOSR/DARPA University Nanosatellite Program. He has been an architect for the SmallSatCEM while on sabbatical at The Aerospace Corporation.